THE ASTROPHYSICAL JOURNAL, 317:987–991, 1987 June 15

SPECTROPHOTOMETRY OF COMETS GIACOBINI-ZINNER AND HALLEY

STEPHEN C. TEGLER[1] AND C. R. O'DELL
Rice University
Received 1986 October 3; accepted 1986 November 26

ABSTRACT

Optical window spectrophotometry was performed on comets Giacobini-Zinner and Halley over the interval 300–1000 nm. Band and band-sequence fluxes were obtained for the brightest features of OH, CN, NH, and C_2, special care having been given to determinations of extinction, instrumental sensitivities, and corrections for Fraunhofer lines.

C_2 Swan band sequence flux ratios were determined with unprecedented accuracy and compared with the predictions of the detailed equilibrium models of Krishna Swamy and O'Dell. We find that these band sequences do not agree with the predictions, which calls into question the assumptions made in deriving the model, namely resonance fluorescence statistical equilibrium. Suggestions are made as to how to resolve this discrepancy.

Subject headings: comets — molecular processes — spectrophotometry

I. INTRODUCTION

The recent perihelion passages of comets Giacobini-Zinner (G-Z) and Halley have justifiably attracted unprecedented attention because of the near passage of multiple spacecraft making in situ measurements and observations. A product of this attention should be an unusually complete set of ground-based observations, about which this brief paper reports in part. The intent of our work was to provide basic spectrophotometry across the optical window with high and well-determined accuracy. Not only are these natural goals to be set, but also very necessary, for many of the previous observations have been of low or uncertain accuracy. As application of spectrophotometry for determination of physical conditions in the cometary coma and of abundances often requires very accurate measurements, much of the previous work on other comets serves little purpose beyond being a guide. We attempted to observe over as wide a wavelength range as possible in order to be able to tie our measurements into those in the satellite ultraviolet and the infrared.

Our special goal was to make definitive measurements for testing the existing theories of resonance fluorescence radiative equilibrium in the cometary C_2 molecule. There has been a basic disagreement between theory and observation for over 20 yr and by now a very detailed and complete theory exists, with the bottleneck being a lack of good observations. Such a discrepancy begs resolution, for disagreement about the processes occurring in one of the most abundant and best observed molecules raises doubts about the basic assumptions made in the interpretation of indirect measurements of comets.

II. OBSERVATIONS

The type of data we sought determined the equipment we used. We wanted to observe both comets with the same system and near the time of the spacecraft flybys, so a southern hemisphere location was demanded. We employed the 1.5 m telescope of the Cerro Tololo Inter-American Observatory in Chile. As we wanted high and well-defined photometric accuracy over a wide wavelength range, we chose the Harvard Scanner, a classical scanning spectrophotometer with two photomultipliers in the plane of the two spectra formed from double entrance apertures. As the separation of the apertures was within the size of the comae, we used only the results of the aperture centered on the nucleus. As such scanners examine only one portion of the spectrum at a time, they do not have the multiplex advantage of more modern devices such as the smoothing image-dissector scanners, but they do have clearly defined spectral purity and high photometric accuracy.

As comets present unusual challenges to the photometrist, a few comments about observing procedures are in order. Because a comet is usually brightest when nearest the Sun, the dark time for its observation is usually short, and the measurements are made at large zenith distances. This means that extinction coefficients and system sensitivities must be made from standard star observations before or after the observing window for the comet. This in turn calls for a carefully prepared schedule of each night's observations, in this case detailed to about 10 minute intervals. We selected our standard stars from the list of Breger (1976), limiting ourselves to the fainter objects as brighter stars could have exceeded the linear range for the pulse-counting system used. The comets move with respect to the normal sidereal drive rate of the telescopes, so guiding was checked frequently in order to hold the brightness center of the coma in the center of the 24″.7 diameter entrance aperture.

Comet G-Z was observed on 1985 September 30 (heliocentric distance 1.09 AU, geocentric distance 0.54 AU) over the wavelength range of 300–570 nm. The calibration stars were 29 Psc, 45 Tau, and 49 Tau. Comet Halley was observed from 300 to 1000 nm on 1986 March 12–14 using the calibration stars θ Vir and σ Ser, with the details of the observations given in Table 1. The exit slot used projected to eight nm in the first order and four nm in the second. The spectra were sampled at intervals of four nm and two nm in the first and second orders, respectively.

Unusual attention was given to the determination of the extinction coefficients, especially in the ultraviolet. For the limited set of observations of comet G-Z we used the standard

[1] Visiting Observer, Cerro Tololo Inter-American Observatory, National Optical Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1
COMET HALLEY OBSERVATIONS

Date	Heliocentric Distance (AU)	Geocentric Distance (AU)	Wavelength Range
1986 Mar 12.4.........	0.87	1.01	300–580 nm
1986 Mar 13.4.........	0.89	0.99	530–1000 nm
1986 Mar 14.4.........	0.90	0.96	300–580 nm

extinction values of Stone and Baldwin (1983) except for wavelengths below 320 nm, which they did not cover. For those wavelengths we determined the extinction coefficients from the 10 observations of the three standard stars, obtaining the results in Table 2.

The more extensive Halley observations allowed an independent determination of extinction. We determined the extinction coefficient at varying intervals, depending on the rate of change with wavelength, and then used the expected behavior to refine the values. The extinction in the telluric line free regions has three major components: gray—due to extinction by dust; Rayleigh—due to scattering by molecules; and absorption—due to the nearby ozone cutoff. The gray component was established from infrared observations to be 0.06 ± 0.02 mag per airmass. The range of wavelengths longward of 320 nm was then assumed to be only the gray plus Rayleigh components, and a wavelength (-4 power) component was fitted to the data to give an extinction coefficient (k_λ mag per airmass) of

$$k_\lambda = 0.06 + 1.175 \times 10^{10}/\lambda^4 ,$$

where the wavelength is in nanometers. The extinction shortward of 320 nm increased rapidly, probably due to absorption by atmospheric ozone. As a good wavelength guide does not exist for this component, it was determined empirically from the standard star observations, with the resulting total extinction coefficients being given in Table 2. These coefficients are probably good to a few hundredths of a magnitude, which is certainly sufficient as the difference of airmasses of the standard stars and the comets was less than one.

The system sensitivities necessary for reducing the comet observations into fluxes were determined from the extinction-corrected standard star observations by using the Breger (1976) designated flux distributions. As those calibrations do not extend to the shortest wavelengths observed in this program, we had to extrapolate the flux beyond the tabulated values. The standards were all spectral types where the distribution curves were well behaved, but we successfully tested our extrapolations by comparison with the stellar atmosphere models of Kurucz (1979). The uncertainties due to this procedure are probably not more than a few percent. The count rate per channel was high, so that the count statistics errors were less than 1%. The scatter of 1.5% in the final results for the sensitivity is probably due to small fluctuations in transparency.

The comet observations could then be corrected for atmospheric extinction and system sensitivity and converted to fluxes. Figure 1 gives a characteristic calibrated second-order spectrum for comet Halley. Figure 1 shows that a strong scattered-light cometary continuum was present. The continuum from superposed sky continuum had already been subtracted from the total comet plus sky signal. The cometary continuum shows the same slight reddening in this wavelength interval that has been seen before (O'Dell 1971; Stokes 1972).

The goal of this program was to obtain fluxes from bands and band sequences, by integrating over the spectral features, after determining the corrections for the continuum. Multiple channels on each side of the spectral features were assumed to be free of emission lines according to high-dispersion spectra of other comets, and the continuum was smoothly interpolated. An additional correction had to be made at this point due to Fraunhofer absorption lines that appear in the solar spectrum and hence also must appear in the scattered-light cometary continuum. This effect was measured by making sky measurements at high signal-to-noise ratio during the twilight, then searching for spectral features, determining their equivalent widths, and then applying the appropriate correction factor to the interpolated cometary continua. The resulting continuum subtracted, integrated fluxes are given in Table 3. As the cometary observations extended over an interval of at most a few hours, we have averaged the results for each date. The dispersion of the results of the brightest features is characteristically about 1.3%–3.7%, while counting statistics alone would predict uncertainties of only 0.5%–1.9%, the additional scatter probably arising from the uncertainties in the extinction corrections, the sensitivities, and the guiding errors as the centrally condensed coma image moved about within the entrance aperture during a spectral scan.

TABLE 2
ULTRAVIOLET EXTINCTION COEFFICIENTS

WAVELENGTH (nm)	k_λ (magnitudes/airmass) Comet G-Z	Comet Halley
304.........	...	2.62 ± 0.20
306.........	2.45 ± 0.08	2.24 ± 0.16
308.........	1.99 ± 0.05	1.96 ± 0.29
310.........	1.77 ± 0.15	1.67 ± 0.26
312.........	1.51 ± 0.08	1.53 ± 0.21
314.........	1.41 ± 0.01	1.43 ± 0.19
316.........	1.24 ± 0.03	1.31 ± 0.13
318.........	1.15 ± 0.03	1.23 ± 0.14
320.........	1.07 ± 0.08	1.11 ± 0.16

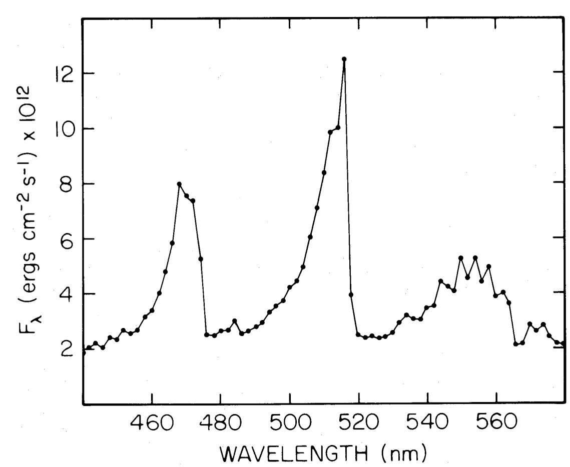

FIG. 1.—The flux distribution with wavelength is shown for a single observation of comet Halley, this plot being characteristic of all of the comet Halley spectral scans.

TABLE 3

BAND AND BAND SEQUENCE FLUXES[a]

Object	Date	OH λ308	NH λ336	CN λ388	C_2 $\Delta V = +1$	C_2 $\Delta V = 0$	C_2 $\Delta V = -1$	CN λ918
Comet G-Z	1985 Sep 30.3	148 ± 40	...	102 ± 30	...	...	...	...
Comet Halley	1986 Mar 12.4	2235 ± 25	148 ± 8	1106 ± 15	654 ± 8	1183 ± 6	603 ± 8	...
	1986 Mar 13.4	...	...	...	...	...	...	168 ± 12
	1986 Mar 14.4	4010 ± 150	247 ± 12	1640 ± 50	936 ± 14	1730 ± 30	848 ± 10	...

[a] Units are 10^{-12} ergs cm^{-2} s^{-1}.

III. DISCUSSION OF C_2

The night-to-night variations in the integrated flux of various molecular emission features are what we have come to accept as normal for comets, especially in the light of the rotating, highly irregular nucleus of comet Halley revealed by the flybys. Of more direct interest to us is the behavior of the Swan band sequence flux ratios. The other molecular fluxes are left for use by other researchers.

Under the assumption of radiative equilibrium of molecular states as determined by resonance fluorescence from sunlight, a quasi-static distribution within the various vibrational levels of the lowest triplet electronic state of C_2 will be established. Stockhausen and Osterbrock (1965) showed that the Boltzmann temperature that corresponds to that equilibrium distribution should be the same as the color temperature of the Sun at the wavelengths dominating the resonance fluorescence. As the relative intensities of the various Swan band sequence flux ratios will vary depending on the population distribution in various vibrational states, observation of the band sequence flux ratios can be a measure of the vibrational temperature. There have now been numerous papers which have established that the expected and predicted ratios do not agree (Mayer and O'Dell 1968; Krishna Swamy and O'Dell 1977; A'Hearn 1975). The development of increasingly complete and detailed computer models for C_2 has recently been summarized by Krishna Swamy and O'Dell (1987). Although their models include many possible transitions, they find that the vibrational population and hence the Swan band sequence flux ratios are primarily determined by the rate at which forbidden transitions occur between the a state, which is the lowest triplet state and the lower level involved in forming the Swan bands, and the X state, which is the lowest singlet level, residing at a slightly lower energy. As the transition moment for these forbidden transitions is unknown, they used the transition moment ($|Re|^2_{a-X}$) as a free parameter. As the rate of a–X transitions increases the vibrational temperature decreases, and the $\Delta v = +1$ band sequences decrease in strength relative to the $\Delta v = 0$ band sequence. For a fixed value of the rate of a–X transitions these transitions should become relatively more important at larger heliocentric distances, where the rate of solar photoexcitations is less, and the vibrational temperature should drop. If enough photoexcitations occur to wipe out any memory of the distribution that existed when the C_2 formed and if collisional exchanges are unimportant, which are the assumptions underlying all of the theoretical work, then all comets at the same heliocentric distance should have the same band sequence flux ratios and these ratios should change with

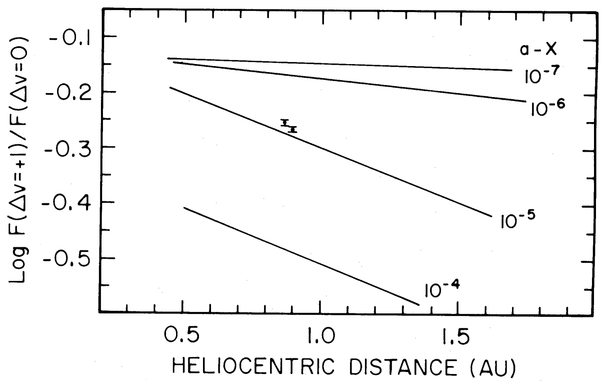

FIG. 2.—The observed comet Halley $\Delta v = 0, +1$ band sequence flux ratios are compared with the theoretical predictions of Krishna Swamy and O'Dell (1987) for various values of the transition moment for the a–X transition.

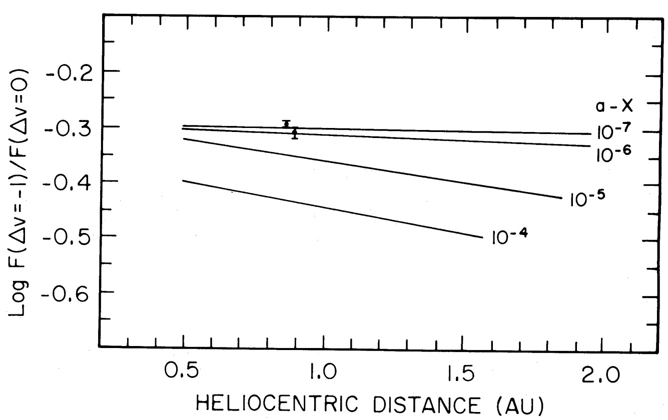

FIG. 3.—The same as Fig. 2 except that the $\Delta v = 0, -1$ flux ratios are shown.

TABLE 4

C_2 BAND SEQUENCE FLUX RATIOS

Date	$F(\Delta V = +1)/F(\Delta V = 0)$	$F(\Delta V = -1)/F(\Delta V = 0)$
1986 Mar 12.4.........	0.553 ± 0.004	0.541 ± 0.005
1986 Mar 14.4........	0.510 ± 0.008	0.491 ± 0.014

heliocentric distance in a smooth fashion. Moreover, the transition moment inferred should be the same, regardless of which band sequence ratio is being considered.

Our observations (Table 4) are compared with the Krishna Swamy and O'Dell (1987) theory in Figures 2 and 3. The very small errors of our observations establish that the necessary transition moment inferred from the $\Delta v = +1$ band sequence is only slightly larger than 10^{-5} atomic units, while that inferred from the $\Delta v = -1$ band sequence is about 10^{-6} to 10^{-7}. This inconsistency means that even the most sophisticated model fails to match the observations, which calls into question the methods and assumptions of the theory.

Such an accusation demands comparison with the results of other observers. By now similar observations exist for a large number of comets, obtained by different methods and at different heliocentric distances. We show in Figures 4 and 5 the results of all of the previous observations cited in the Krishna Swamy and O'Dell (1987) paper, using their symbol code, but we have also added the results of Gebel (1970) for comets 1967n, 1968b, and 1968c (symbols N, B, and C, respectively). The conclusions would be the same if we added or used only the results of the senior author (C. R. O.) and his collaborators (Mayer and O'Dell 1968; O'Dell 1971), which we have not shown in order to avoid arguments of systematic errors in the method of observation and analysis. Unfortunately, the only common feature of the observations is the lack of a careful analysis of the errors of the results. However, the average of the many observations at the smaller heliocentric distances argues for the same conclusion as our few accurate observations. A realistic measure of the accuracy of the previous results is the scatter shown within a given comet, where we can use theory as a guide and expect that the ratios should be nearly constant at a given heliocentric distance. It is the large heliocentric distance observations that could change the final picture. If the observations of Gebel are correct, then this would argue that the band sequence flux ratios are constant with heliocentric distance forcing the conclusion that radiative leaking between the *a* and *X* states is not the primary factor in suppressing the vibrational temperature. A leaking through the series of transitions *a*–*d*–*c*–*X* would not show a heliocentric dependence in the vibrational temperature, but Krishna Swamy and O'Dell's (1987) models show that the population distribution change through this chain of transitions is small.

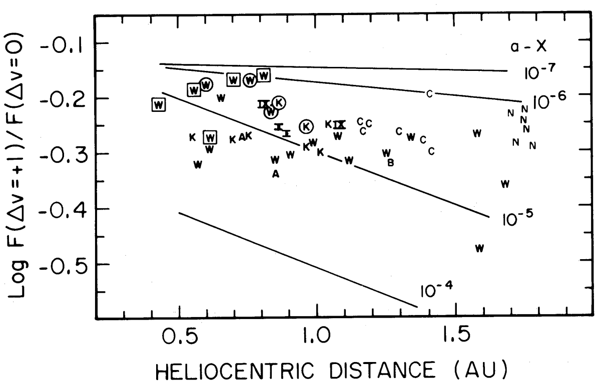

FIG. 4.—The same as Fig. 2 except that all of the data depicted in Fig. 2 of Krishna Swamy and O'Dell (1987) have been added, using the same symbols of that paper, in addition to the results of Gebel (1970) cited in the text.

What can be the source of the disagreement between the theory and observations? Certainly it cannot be the completeness of the model used, for the theory employs not only the major, but also the minor, transitions and treats as free parameters the rates at which nonobserved transitions occur. Moreover, the consideration of 14 vibrational levels in each electronic state is more than adequate as the higher levels have a negligible fraction of the population. It seems unlikely that the answer lies in errors of the absolute value of the molecular constants, as the discrepancy of theory and observation is present even in the simple calculations of Stockhausen and Osterbrock (1965) who considered only the *a* and *d* states. Perhaps we are seeing the residual effects of the population distribution present when the C_2 was formed, which would apply if there is an inadequate number of photoexcitations-decays to wipe out the memory of the original distribution. Arpigny (1965) argues that at 1 AU heliocentric distance a

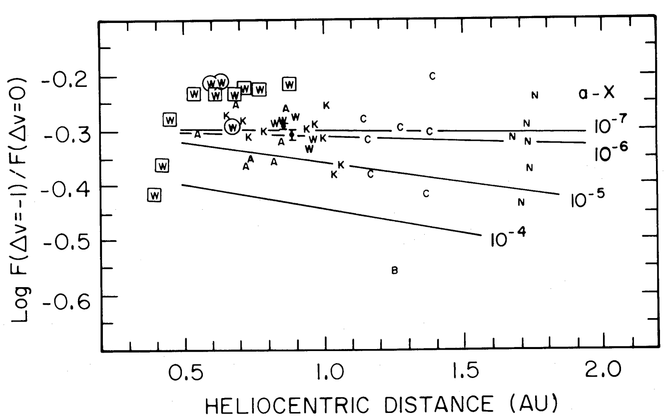

FIG. 5.—The same as Fig. 4 except that the $\Delta v = 0, -1$ flux ratios are shown.

photoabsorption occurs about every 10 s, while O'Dell and Osterbrock (1962) show that at the same distance the photodissociation lifetime is about 10^6 s and a photodissociation length about 10^6 km, so that each molecule fluorescences about 10^5 times; the more recent work of Combi and Delsemne (1986) gives 10^5 s, either of which should be adequate for establishing a population distribution determined by radiative processes rather than the chemistry of the origin. This conclusion would apply if we had measured an outer region of the coma, but this is not the case, as our 18,000 km diameter aperture was centered on the nucleus. As the referee has pointed out, this means that even after allowing for integrations along the line of sight, the emission is characteristic of the population distribution after much less than 10^4–10^5 times. Even that large number will apply only to the strongest Swan bands, with the much higher states fluorescing less and the weak ground-singlet states even less still. We need a time-dependent resonance fluorescence model to test this hypothesis. We are interpreting only the triplet population and if the original population was primarily in the singlet states, the slow rate of leaking to the triplets would prevent establishing a radiative equilibrium in the triplets. If this is the case, the ratio of singlet-to-triplet band fluxes would be much stronger than predicted by the radiative models and the total abundance of C_2 would be much greater than traditionally determined.

One must also critically consider the accuracy of the band sequence flux ratios in terms of nonrandom errors. The most worrisome effect would be contamination by other emission bands, in particular the CO^+ bands might affect the $\Delta V = +1$ and O ratios and the NH_2 bands might affect the $\Delta V = -1$ flux. We have examined higher resolution spectra obtained in the same period by Susan Wyckoff and Peter Wehinger and find that clearly the contamination by CO^+ cannot be more than a few percent. The effect of NH_2 on $F(\Delta V = -1)$ is possibly 10%, that is, the $\Delta V = -1$ bands sequence may contain as much as a 10% contribution due to the bands of NH_2. The maximum correction to $\log F(\Delta V = 1)/F(\Delta V = 0)$ would be -0.046, which would move the observations toward the same Krishna Swamy and O'Dell model as the $\Delta V = +1$ observations but would not close the gap.

More observations are badly needed. We need to know if there is an intrinsic dispersion of Swan band sequences between various comets, how the Swan band sequences vary with heliocentric distance (best done by monitoring a single comet), and what is the Swan band sequence ratio for very large heliocentric distances. The effects of populations reflecting conditions of formation could be determined by relative flux ratios at the inner and outer parts of the coma. Accurate ratios of triplet and singlet band sequences such as Phillips/Ballik-Ramsay or Mulliken/Swan need to be determined, to resolve the question of the relative populations of the triplet and singlet states (Krishna Swamy and O'Dell 1979, 1981). We had prepared to make just these observations during this same apparition of comet Halley, but the delay of the first launch of the Astro mission because of the accident with the Space Shuttle and some equipment problems with the Kuiper Airborne Observatory precluded obtaining any results. Perhaps other observers have these data in hand already and can use this work and the theoretical studies to resolve this basic discrepancy in understanding cometary C_2.

This work was supported in part by National Aeronautics and Space Administration grant NAG8-485 and National Science Foundation grant AST-8505031 to Rice University.

REFERENCES

A'Hearn, M. F. 1975, *A.J.*, **80**, 861.
Arpigny, C. 1965, *Ann. Rev. Astr. Ap.*, **3**, 351.
Breger, M. 1976, *Ap. J. Suppl.*, **32**, 7.
Combi, M. R., and Delsemne, A. H. 1986, *Ap. J.*, **308**, 472.
Gebel, W. L. 1970, *Ap. J.*, **161**, 765.
Krishna Swamy, K. S., and O'Dell, C. R. 1977, *Ap. J.*, **216**, 158.
———. 1979, *Ap. J.*, **231**, 624.
———. 1981, *Ap. J.*, **251**, 805.
Krishna Swamy, K. S., and O'Dell, C. R. 1987, *Ap. J.*, **317**, 543.
Kurucz, R. L. 1979,, *Ap. J. Suppl.*, **40**, 1.
Mayer, P., and O'Dell, C. R. 1968, *Ap. J.*, **153**, 951.
O'Dell, C. R. 1971, *Ap. J.*, **164**, 511.
O,Dell, C. R., and Osterbrock, D. E. 1962, *Ap. J.*, **136**, 559.
Stockhausen, R. E., and Osterbrock, D. E. 1965, *Ap. J.*, **141**, 287.
Stokes, G. M. 1972, *Ap. J.*, **177**, 829.
Stone, R. P. S., and Baldwin, J. A. 1983, *M.N.R.A.S.*, **204**, 347.

C. R. O'Dell: Department of Space Physics and Astronomy, Rice University, P.O. Box 1892, Houston, TX 770251

Stephen C. Tegler: Astronomy Group, Physics Department, Arizona State University, Tempe, AZ 85287